STREAK TUBE IMAGING LIDAR (STIL) FOR 3-D IMAGING OF TERRESTRIAL TARGETS

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ABSTRACT

The Streak Tube Imaging LIDAR (STIL) is a patented active imaging system using a pulsed laser and a streak tube receiver to produce high resolution 3-D range and intensity imagery. The laser beam is diverged in the cross-track (azimuth) direction into a fan beam which is projected into the scene as a cross-track line. The backscattered light from the scene is imaged onto the streak tube's photocathode, and is time (range) resolved by electrostatically sweeping the resultant electron beam across the streak tube's phosphor screen to generate from each laser pulse a continuous intensity-range-azimuth image which is captured by a CCD array fiber optically coupled to the phosphor screen. A high resolution 3-D image of the scene is produced from multiple sequential frames formed by repetitively pulsing the laser in synchrony with the CCD frame rate as an airborne platform "push broom" scans or as a single-axis scanner on a ground-based platform scans the laser fan beam over the scene. The frames are registered using data from an inertial measurement unit (IMU) to compensate for platform motion. The system can also use GPS data with the 3-D data from the sensor for absolute geolocation of points in the scene.

Ground based field tests were conducted with STIL operating at 128 range by 512 azimuth pixels over 12.6^o and 47.6^o azimuthal fields-of-view (FOV). Targets included a HMMWV, a C-130 transport plane, two range resolution panels, and a contrast resolution panel. Data was collected at ranges from 100 m to 1 km. Data from these tests demonstrating achievement of pixel limited image resolution and 6 inch range resolution are presented.

Airborne field tests were conducted at altitudes of 800 - 1000 feet in a Partenavia Explorer fixed wing aircraft. Imagery was collected at 256 range by 256 azimuth pixels over a 12.6^o FOV. In these tests, the STIL was integrated with a real-time kinematic (RTK) GPS system and a C-MIGITS IMU to demonstrate absolute geolocation of surveyed ground features to meter scale accuracy. Terrestrial features imaged in these tests included buildings, runways, and aircraft. Data from these tests demonstrating achievement of absolute geolocation of surveyed ground features to meter scale accuracy laterally and decimeter scale accuracy in elevation are presented.

Ongoing and future efforts for terrestrial applications of STIL include developing a compact, lightweight STIL system, developing real-time 3-D image processing for STIL, improving the resolution to 256 range by 1024 azimuth pixels, developing a 1.5 micron wavelength STIL, and commercializing an airborne STIL for terrestrial surveying and bathymetry.

*E.B. Schibley recently left Arete Associates to work at home. However, she still provides consulting services to Arete Associates through a consulting agreement.

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1.0 INTRODUCTION

Until recently, conventional airborne and terrestrial ladars have mostly been single detector systems which form 3-D images via 2-D scanning. Recently ladars with receivers using a linear PIN or APD array with 1-D scanning have been built. 2-D PIN and APD array receivers for scannerless imaging ladars are under development.[1] To date the angular resolution of 1-D and 2-D detector arrays for ladars have been limited by the difficulty in effectively determining time-of-flight in all receiver channels simultaneously, and efficiently reading out the signals from many channels at a high rate to obtain high resolution images at reasonable frame rates over wide fields-of-view. A 32 x 32 pixel 2-D APD array ladar receiver has been built and tested.[2] 2-D APD array designs of up to 128 x 128 pixels have been proposed. These array sizes are sufficient for narrow field-of-view (FOV) or coarse resolution applications, but are insufficient for wide FOV and high resolution imaging applications. For both linear and area array receivers, multi-channel, extremely high speed (gigahertz) capture and digitization electronics are required to provide both range and intensity images.

Sandia National Laboratories has demonstrated a scannerless system based on gain modulation of an image intensifier, modulation of the laser output, and determination of range via detection of the phase between the return signal modulation and the image intensifier gain modulation by the resultant modulation of the image intensity.[3] This method requires acquisition of several modulated laser illuminated frames and one or more unmodulated or differently modulated frames to differentiate intensity modulations due to range variations from those due to reflectance variations in the scene. Relatively long frame integration times have so far limited the range performance of the Sandia approach in day time. Long frame integration times may also limit resolution for imaging from high speed platforms due to the motion induced blurring during the frame integration time.

Arete' Associates' patented **S**treak **T**ube **I**maging **L**idar[4] (STIL) is an innovative 3-D imaging ladar system based on a unique application of mature technologies. STIL has demonstrated sub-nanosecond range measurement accuracy (< 5 cm) over a wide azimuthal field-of-view (FOV) (~47^{o}) with high angular resolution (512 pixels). The number of azimuth pixels and the frame rate obtainable are limited only by the size and frame rates of available CCD arrays which are used to read out the intensity and range data in the STIL concept. The extremely short dwell time per pixel (~ 1 ns) in the STIL concept provides robust day and night operation.

1.1 Streak Tube Imaging Lidar (STIL) Concept Description

STIL is an active imaging system using a pulsed laser transmitter and a streak tube receiver to time/range resolve the backscattered light as shown in Figure 1. The laser beam is diverged in one dimension using a cylindrical lens and/or diffractive optic to form a fan beam (wide azimuth (cross-track), narrow elevation (along track) beam divergences) which is projected into the scene as a line. The backscattered light from the objects and the terrain intersecting the fan beam is imaged by a lens onto a slit in front of the streak tube photocathode, and is time /range resolved by electro-static sweep within the streak tube, generating an intensity-range-azimuth image on each laser pulse. This intensity-range-azimuth image is captured by a CCD array fiber optically coupled to the phosphor screen of the streak tube. Figure 2 shows a single intensity-range-azimuth image captured by the STIL receiver, and Figure 3 shows the range-azimuth sampling grid provided by the STIL receiver for each frame. The range to a surface point in the intensity-range-azimuth image is determined by a surface finding algorithm which determines the position of the peak of the output of a matched filter convolved with the intensity profile in the time/range direction. The signal level in the pixel corresponding to this peak provides a measure of the reflected intensity of the imaged surface at that point. By synchronizing the pulse repetition rate of the laser and the frame rate of the CCD array with the speed of a moving host vehicle, or with the scan rate of a single-axis scanner, the along track or elevation dimension is swept out. The successive frames, which have been processed to find the surface contour in each frame, are "stacked" together to form the high resolution 3-D image of the scene.

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[1] Lewotsky, Kristin. "Receiver yields images from a single pulse," Laser Focus World, June 1997, pp. 55-60.
[2] Heinrichs, R.M., B.F. Aull, M.A. Albota, D.G. Fouche, and S. Kaushik, "Development and Testing of a 32x32 Avalanche Photodiode Array with Integrated Timing Circuitry for 3-D Imaging Laser Radar," Proceedings of the 1999 Meeting of the IRIS Specialty Group on Active Systems, 24-26 February 1999.
[3] Sackos, John, B. Bradley, R. Nellums, and C. Diegert, "The Emerging Versatility of a Scannerless Range Imager," SPIE Vol. 2748, 1996, pp. 47-60.
[4] Patent Number 5,467,122, issued 14 November 1995.

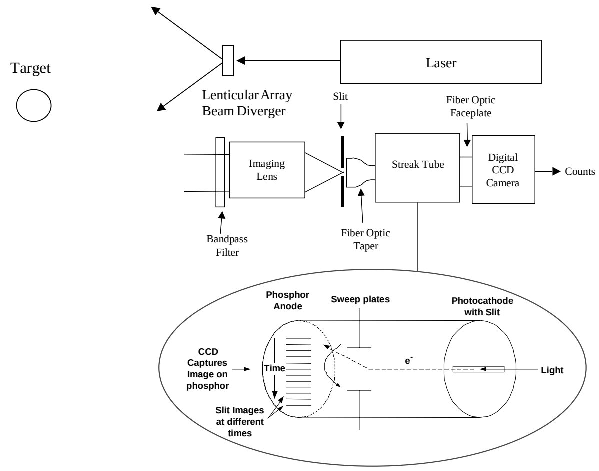


Figure 1. Streak Tube Imaging Lidar (STIL) Concept of Operation

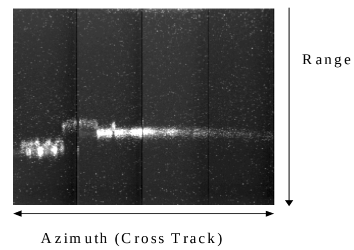


Figure 2. A single unprocessed Intensity-Range-Azimuth image frame captured by the STIL receiver.

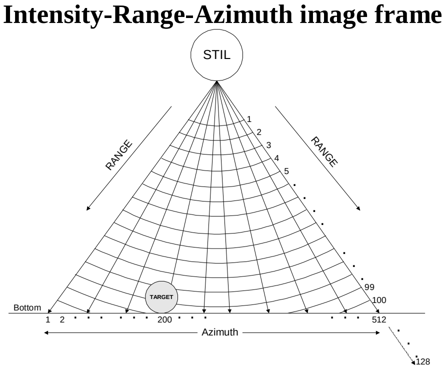


Figure 3. Range-azimuth sampling grid provided by each STIL frame.

Advantages of STIL include:

(1) **No Scanner** required for operation from a moving vehicle

(2) **High Resolution over Wide FOVs**

- Limited only by the streak tube spatial resolution and CCD array size
- Currently available components provide **up to 1024 azimuth pixels**

(3) **Multi-channel, ultra-high speed temporal sampling is integral to the receiver concept**

- 1000+ channels of 12-bit signal digitization at adjustable sampling rates up to 10+ GHz
- No multi-channel, high speed transient digitizers required

(4) **Commercial-Off-The-Shelf (COTS) Transceiver Components:** Streak tubes, CCD arrays, and moderate power solid state lasers

(5) **Robust Day/Night Operation**

- Short dwell time per pixel (~ 1 ns) during streaking yields low solar background & dark current noise
- Pulsed illumination provides signal independent of ambient illumination conditions

(6) **Scaleable** resolutions in three dimensions to meet the requirements of various applications

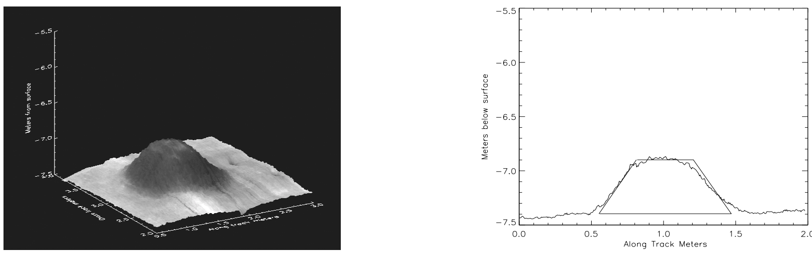
(7) **Imaging through Camouflage and Obscurants**

- Continuous sampling of returns over the range window
- Sweep delay offsets range window to eliminate near field scatter from the image

2.0 STIL TECHNOLOGY STATUS

The STIL system is based upon a unique application of relatively mature technology. The major components, including the streak tube, CCD array, and laser, are all mature, commercially available technologies. In 1994, the Office of Naval Research (ONR) awarded a multi-year contract to Areté Associates to develop, demonstrate, and evaluate a STIL prototype system for high resolution ocean remote sensing and shallow water mine Electro-Optic IDentification (EOID). During 1995, a STIL laboratory prototype was designed, fabricated, integrated, and characterized by laboratory and field testing. The STIL prototype met or exceeded all specifications.

Further field tests of the STIL system in ocean and coastal environments during FY96 through FY99 demonstrated the capability of STIL to provide high resolution 3-D imagery for such diverse applications as bathymetry and precise target location and identification.[5] Figure 4 shows a 3-D reconstruction of an underwater minelike target at 25 foot depth from STIL EOID data collected in ocean testing.



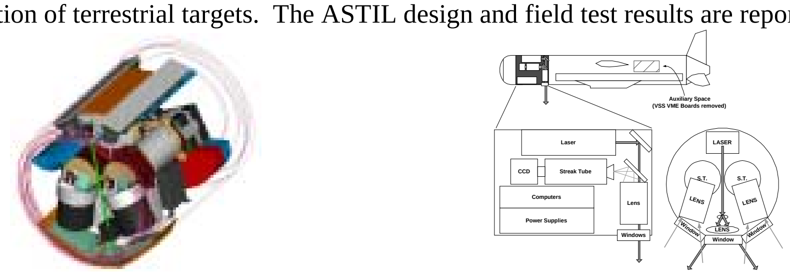
(a) (b)

Figure 4. 3-D images of an underwater minelike target reconstructed from STIL data taken with the target at 25' depth in ocean testing. (a) Contrast data mapped onto the 3-D surface (b) 1-D cut through the range image compared to the actual target profile showing an excellent match.

Areté was awarded a second three year contract by ONR in 1998 to address engineering issues associated with vehicle integration and operational deployment, including development, integration, and full scale ocean testing of a wide FOV, dual receiver, EOID system in the VSS section of the AQS-20 tow body. A 3-D Pro Engineering layout of the two receiver STIL EOID sensor and its location in the towbody are shown in Figure 5. This program includes development and implementation of real-time processing algorithms. The AQS-20 compatible STIL EOID prototype is undergoing initial sea trials in the towbody in the Gulf of Mexico during CY2000.

In December of 1999, Arete Associates was awarded a two year contract to produce two Engineering Manufacturing & Development (EMD) prototype STIL-EOID systems for Raytheon's AQS-20(X) mine detection and identification towbody system.

Areté Associates has also designed and built an airborne streak tube imaging lidar (ASTIL) system under IR&D and ONR funding for underwater mine detection, bathymetry, terrestrial mapping, and terrestrial target imaging. The ASTIL breadboard prototype was used in ground based and airborne field tests to demonstrate 3-D imaging and geolocation of terrestrial targets. The ASTIL design and field test results are reported in this paper.



(a) (b)

Figure 5. (a) 3-D ProEngineer model of the two receiver STIL EOID system (b.) STIL deployed in the 15.5" diameter by 19.5" long VSS section of the AQS-20 towed underwater vehicle for mine identification.

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[5] McLean, John W. and James T. Murray. "Streak-tube lidar allows 3-D ocean surveillance," Laser Focus World, January, 1998, pp.171-176.

3.0 STIL FOR MISSILE SEEKER AUTONOMOUS TARGET ACQUISITION

In June of 1999, Arete Associates was awarded a Phase I SBIR contract by the Munitions Directorate of the Air Force Research Laboratory. The objective of Phase I was to demonstrate the feasibility of the STIL concept to meet the 3-D imaging requirements for missile seeker Autonomous Target Acquisition/Recognition (ATA/R).

The Phase I field test and data analysis results directly demonstrated STIL's achievement of 3-D range and intensity imaging with resolutions in all three dimensions comparable to those required for missile seeker ATA/R at significant stand-off ranges. For the Phase I ground based static field tests, the existing ASTIL breadboard prototype was modified to operate over either a moderate field-of-view (12.6^{o}) (MFOV) or a wide field-of-view (47.6^{o}) (WFOV) with software selectable range-azimuth frame sizes of 256 range by 256 azimuth or 128 range by 512 azimuth pixels. A single-axis elevation scan mirror was added to the ASTIL prototype for the static ground tests. The ASTIL breadboard modified for missile seeker ATA/R proof-of-principle tests is called MSTIL to distinguish between the original and modified prototypes. During Phase I, the MSTIL data was processed off-line to produce the reconstructed 3-D range and intensity images shown in this paper. However, real-time data processing and 3-D image construction are being developed under the EOID program, and will be incorporated into further MSTIL development, if funded.

3.1 Scenario and Requirements

The anticipated requirements for missile seeker ATA/R are based on information provided by Capt. Shaun R. Hick of the Munitions Directorate, Eglin, AFB and the Supplemental Information Annex to the PRDA (V2) for the P-LOCAAS program. Capt. Hick described a wide area search scenario in which a miniature cruise missile autonomously searches for targets using the ladar's high resolution 3-D imagery for robust ATA/R (Figure 6).

The mission requirements that drive the design of the MSTIL are

1. **Search Area**: > 50 km^2 over a flyout range of 100 km (implies FOV > 30.6^{o}) at a speed of 200 knots (103 m/s) with an acquisition slant range of 1 km to 2 km
2. **Resolution**: From 0.4 mrad to 0.8 mrad in azimuth and along track over a wide FOV and at 200 knots forward speed ; 6 " range resolution
3. **Acquisition Range**: 1 to 2 km from 3000 ft. altitude
4. **Real-time 3-D Image Update**: 5 - 10 Hz 3-D frame update rate

Laboratory and field test results indicating the 3-D range and intensity imaging capabilities of the MSTIL breadboard are presented in this paper in a subsequent section. These test results show that the Phase I objectives were met. The Phase I results provide a strong foundation for the development and testing of a higher resolution Airborne MSTIL brassboard prototype with real-time processing, if further development is funded.

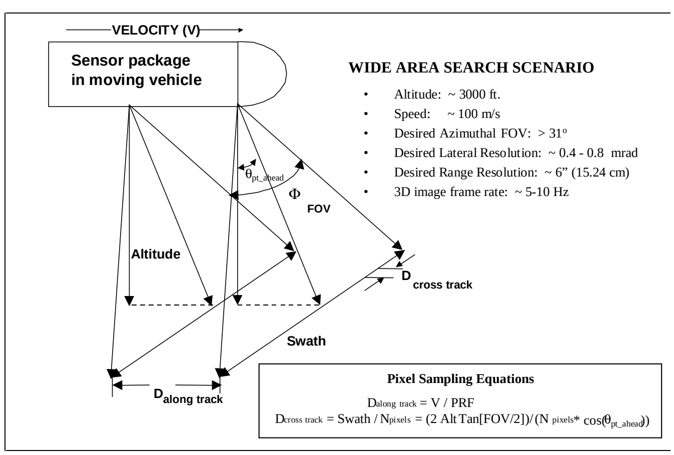


Figure 6. Streak Tube Imaging Lidar (STIL) imaging geometry for wide area search.

3.2 Phase I MSTIL Breadboard Description

The Phase I MSTIL breadboard consists of an operator station containing the operator interface and control computer, laser power supply, laser water cooler, digital delay pulse generator, power supplies, and video monitor, and a sensor rack containing the Silicon Mountain Designs (SMD) CCD array camera and power supply, Hamamatsu C4187 streak camera with slit mount and power supply, receiver lens, narrow band optical filter, Big Sky CFR200 doubled Nd:YAG laser, beam expander/collimator, turning/alignment mirrors, and transmitter beam shaper. For the static ground tests, the sensor rack was mounted on the top of a wheeled cart. The transmitter and receiver were positioned over an aperture in the cart's upper shelf and pointed down to access the scan mirror on the lower shelf. The scan mirror was mounted on a Newport computer controlled motorized rotation stage which provides single-axis (elevation) scanning. A Jewell precision inclinometer was attached to the scan mirror to provide scan mirror angle data. The sensor rack was connected to the operator rack via data and power cables, and via the laser coolant water lines. The inclinometer data was read via a cable connected to a National Instruments data acquisition board. The scanner was connected to a scanner control computer via cables. Table 1 shows the relevant system parameters for the MSTIL Phase I breadboard and those anticipated for the proposed MSTIL brassboard, if the brassboard development is funded.

Table 1. MSTIL System Parameters achieved in Phase I and proposed for the brassboard.

PARAMETER	PHASE I MSTIL BREADBOARD	MSTIL BRASSBOARD
FOV	**Moderate FOV**: 12.6^o **Wide FOV**: 47.6^o	**Wide FOV**: 35.5 ^{o}
Azimuth/Cross Track Resolution	**Moderate FOV**: 0.43 mrad (512 pixels) **Wide FOV**: 1.72 mrad (512 pixels)	**Wide FOV**: 0.625 mrad (1024 az. pixels over 35.5^o)
Elevation/Along Track Resolution	Varied with scan rate.	Varies with forward speed: at 103m/s and 150Hz, 0.67m at 1km
Range Accuracy	6"	6"
Maximum Range	**Moderate FOV**: 1 km **Wide FOV**: 200 m	**Wide FOV**: 1 km
Transmitter Output Pulse Energy Average Power	172 mJ 1.72 W	500 μJ 10 W
Transmitter Output Pulse Width	10 ns	8 ns
Pulse Repetition Frequency	10 Hz	20 KHz
Wavelength	532 nm	532 nm
Clear Aperture Diameter	**Moderate FOV**: 100 mm **Wide FOV**: 35.7 mm	50 mm
Eyesafety	**NOHD MFOV**: 510 m **NOHD WFOV**: 129 m	**NOHD**: 52 m
Frame Rates: Intensity-Range-Azimuth Image 3-D Image Frames	 10 Hz Processed Offline	 150 Hz Real-time scrolling at 150 Hz
Range-Azimuth Frame Pixel Format	128 range x 512 azimuth or 256 range x 256 azimuth	256 range x 1024 azimuth

3.3 Phase I MSTIL Field Test Setup

The static ground tests for Phase I were performed at Davis Monthan AFB in Tucson, AZ with the MSTIL breadboard sensor rack cart mounted on a scissor lift. The lift allowed the sensor to be positioned above ground vegetation. The single-axis elevation scan mirror scanned the fan beam across the targets. The operator station was set up in a cargo van for the tests. The sensor rack cart mounted on the scissor lift in front of the van is shown in Figure 7, and a typical target field setup used in the testing is shown in Figure 8.

The first MSTIL imagery was taken at short range (~60 m). Subsequent MSTIL breadboard imagery was collected at ranges from 100 m to 1 km. The target set consisted of a contrast resolution panel, two range resolution panels (one 12" deep and the other 6" deep), and a HMMWV. The bars or slots on the resolution panels were 10 cm

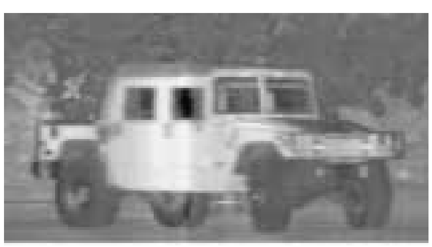
and 15 cm wide. A 20 cm square was also on the panels. A 30 cm wide white area and an adjacent 30 cm black area on the contrast panel allowed measurements at the corresponding spatial frequency to be made. Grounded C-130 transport airplanes were also available as targets of opportunity at a range of 1 km.

Figure 7. MSTIL breadboard sensor rack on a scissor lift for the Phase I ground tests.

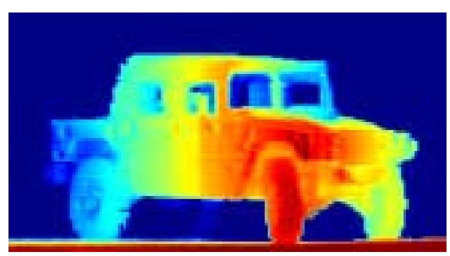
Figure 8. Typical target field setup for MSTIL breadboard Phase I ground tests at Davis Monthan AFB. From left to right, the targets are a HMMWV, a range resolution panel, and a contrast resolution panel.

3.4 Phase I Field Test Results

Figure 9 shows intensity and range images of a HMMWV target reconstructed from MFOV (12.6^{o}) MSTIL data collected at 60 m range in the first field test of the MSTIL breadboard. Images of the HMMWV were also collected at 100 m and 150 m ranges. Figure 10 shows reconstructed intensity and range images of the HMMWV taken at 150m with the MFOV MSTIL. A 3-D image of the HMMWV with the intensity image overlaid onto the 3-D reconstruction is also shown in this figure.



(a.)

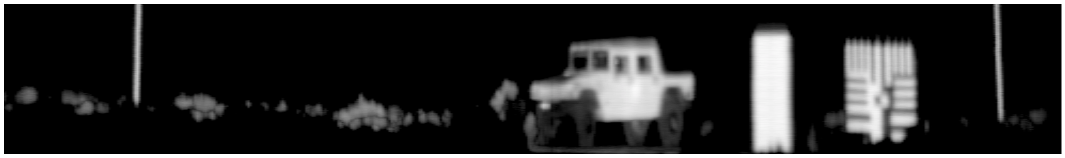


(b.)

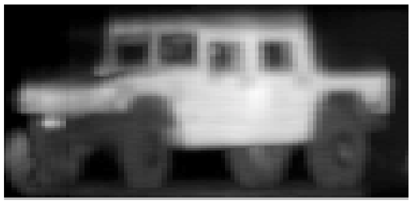
Figure 9. (a.) Intensity image of a HMMWV at 60 m range reconstructed from MFOV (12.6^{o}) MSTIL data. (b.) Range image of a HMMWV at 60 m range from MFOV MSTIL data (original in pseudo-color).

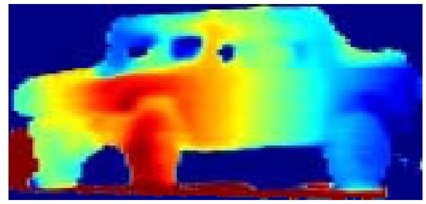
Figure 11 shows intensity and range images of the HMMWV taken with the WFOV (47.6^{o}) MSTIL breadboard at 100 m range during static ground tests.

Figure 12 shows the cut-out of the WFOV mode image of the HMMWV at 200 m range with the intensity image overlaid on the 3-D image. In this image, the intensity image was smoothed by interpolation before being overlaid on the 3-D image. This image shows that the vehicle shape is well defined at this range, but some internal details are not resolved. This is to be expected since the pixel size at this range is 34.4 cm (13.5 inches), corresponding to about 9 pixels across the target length for this three-quarter aspect.

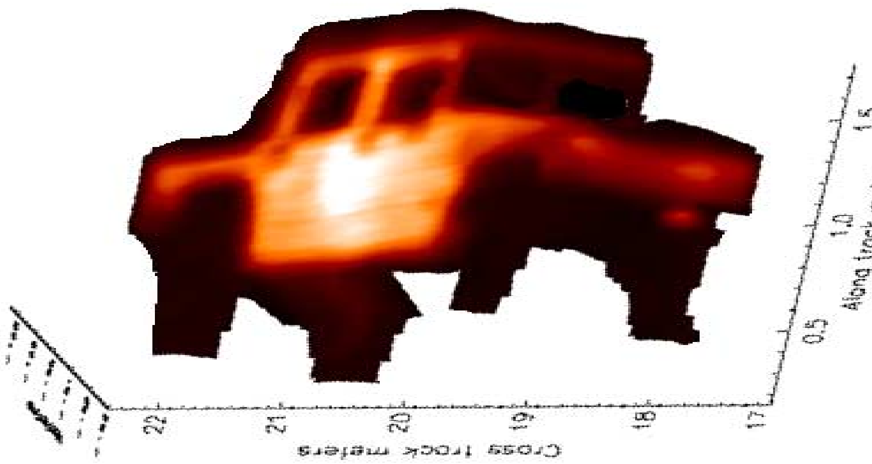


(a.)





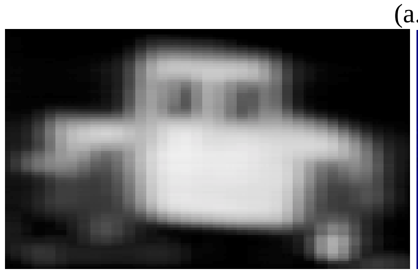
(b.) (c.)

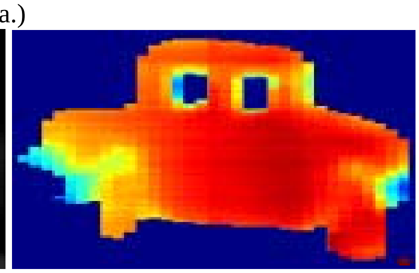


(d.)

Figure 10. (a.) Intensity image of the target field (HMMWV, range resolution panel, and contrast resolution panel) at 150 m range taken by the MFOV MSTIL (512 pixels in azimuth) (b.) Zoomed cut-out intensity image of the HMMWV at 150 m (c.) Range image of the HMMWV at 150 m (original in pseudo-color). (d.) Intensity image overlaid on 3-D image of the HMMWV at 150 m (black is low and white is high intensity).

(a.)





(b.) (c.)

Figure 11. (a.) Intensity image of the target field at 100 m range taken by the WFOV (47.6^{o}) MSTIL (512 pixels in azimuth) (b.) Cut-out of the intensity image of the HMMWV at 100 m in WFOV mode (c.) Range image of the HMMWV at 100 m in WFOV mode (original in pseudo-color).

Figure 12. Intensity image overlaid on the 3-D reconstruction of the HMMWV at 200 m (black is low and white is high intensity). This image was taken in WFOV mode (47.6^o FOV).

Figure 13 shows an intensity image of the contrast panel with profiles in azimuth and elevation reconstructed from data taken with the MFOV MSTIL breadboard at a range of 150 m. The small size of the resolution panel limited its use beyond 150 m. The panel allows measurements of contrast modulation at spatial frequencies corresponding to 10 cm, 15 cm, 20 cm, and 30 cm widths. Also shown in this figure is measured contrast modulation for both the MFOV and WFOV MSTIL breadboard configurations compared to a gaussian contrast transfer function (CTF) with a sigma corresponding to $0.42*2*\Delta\theta_p$, where $\Delta\theta_p$ is one pixel width in azimuth ($\Delta\theta_p$ corresponds to 0.43 mrad for the MFOV and 1.72 mrad for the WFOV).[6] The general agreement between the gaussian CTF and the data demonstrates that pixel limited resolution was achieved for both FOVs.

Range resolution was also verified in the ground tests using two range resolution panels. Each range resolution panel is a plywood box of a specified depth with 10 cm, 15 cm, and 20 cm slots cut in the top panel. One range resolution panel is 12" deep and the other is 6" deep. Figure 14 shows the range image of the 6" deep range resolution panel at 150 m range from MFOV MSTIL data. Azimuth and elevation profiles of the range modulation across the panel are also shown in this figure. From these profiles it is clear that 6" range resolution was achieved for the 15 cm wide slot (1 mrad at 150 m) in the elevation (scan) direction.

Long range (1 km) image data was collected with the MSTIL breadboard in the MFOV configuration. The targets imaged in these long range tests were C-130 transport aircraft. Figure 15 shows 3-D images of a C-130 aircraft at 1 km range reconstructed from data collected using MSTIL in MFOV mode during the ground tests.

These test results indicate that Arete Associates' MSTIL breadboard has demonstrated 0.43 mrad cross-track pixel limited resolution and 6" range resolution in MFOV mode, and 1.72 mrad cross-track pixel limited resolution in WFOV mode. The Phase I MSTIL breadboard operating in MFOV mode has also demonstrated high resolution 3-D imaging of targets at 1 km range.

During the static ground based testing at Davis Monthan AFB and in flight tests over California for terrestrial mapping applications (described in section 4), we also collected initial data demonstrating the feasibility of using STIL to penetrate camouflage and obscurants. Raw Intensity-Range-Azimuth frames of the HMMWV behind a camouflage net and of a power plant building roof line under a steam cloud are shown in figure 16. Returns from the camouflage net and the HMMWV behind it are clearly detectable. Both the steam cloud and the building roof line beneath the cloud are detectable as shown by both the intensity-range-azimuth image and the intensity profile along the range direction through the steam cloud and the building roof line, also shown in figure 16. We are in the process of developing algorithms to reconstruct 3-D volumetric images for imaging the 3-D cloud profile and for imaging through obscurant clouds, and to reconstruct multiple surfaces from multiple range returns for imaging through camouflage.

[6] Lloyd, J.M., Thermal Imaging Systems, New York: Plenum Press, 1975, p. 96, equation 3.38.

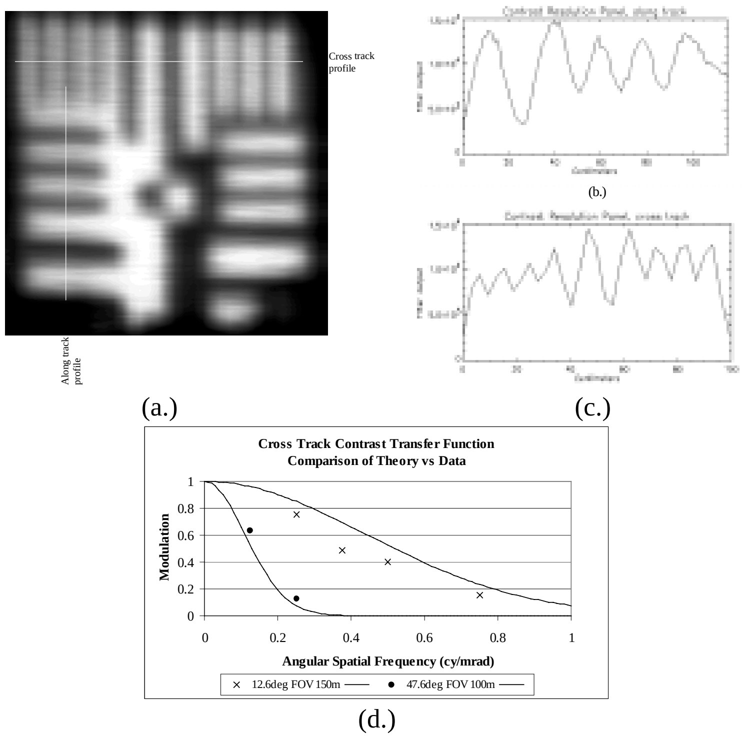


Figure 13. (a.) Intensity image of the contrast resolution panel reconstructed from MSTIL data collected at 150 m range. (b.) Elevation profile across the panel showing the modulation produced by the bars. (c.) Azimuth profile across the panel showing the modulation produced by the bars. (d.) Measured cross track contrast modulation from both the MFOV and the WFOV data compared to the theoretical Gaussian CTF for pixel limited resolution.

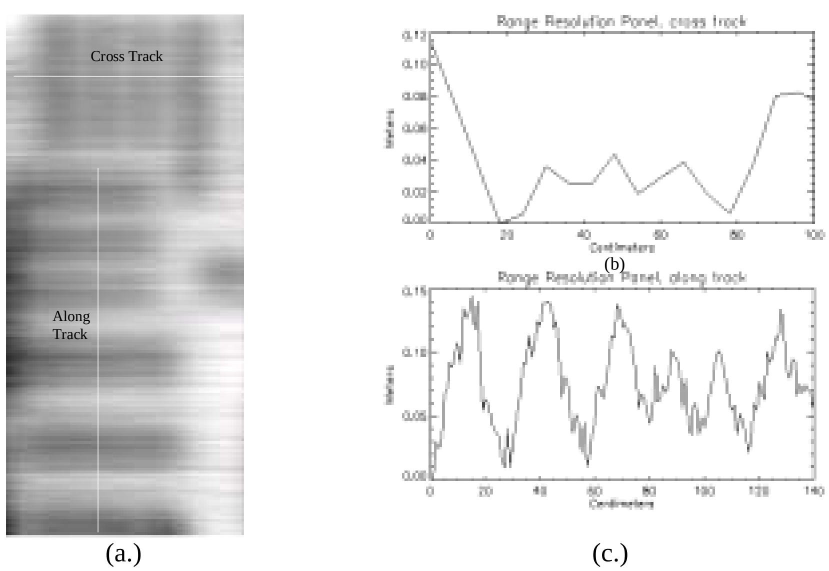


Figure 14. (a.) Range image of the range resolution panel taken at 150 m (range is encoded as grayscale with white being closest and black being furthest away) (b.) Azimuth range profile across the range resolution panel (c.) Elevation range profile across the range resolution panel.

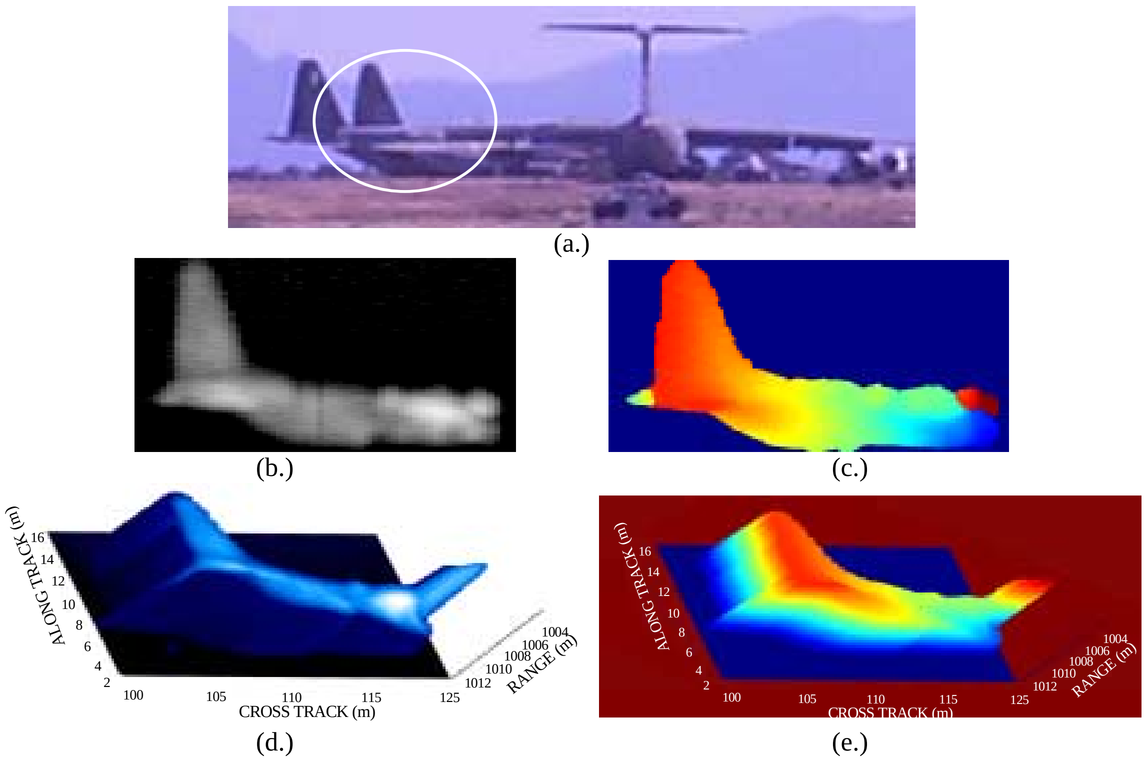


Figure 15. (a.) Photograph of the C-130 transport plane at 1 km range (the circle indicates the region imaged by MSTIL since the area forward of the aircraft's wings was obstructed by objects at closer ranges) (b.) Intensity image of the C-130 at 1 km reconstructed from MFOV MSTIL data (c.) Range image of the C-130 at 1 km reconstructed from MFOV MSTIL data (original in pseudo-color) (d.) Intensity image overlaid on the 3-D projection of the C-130 reconstructed from MSTIL data (e.) Range map overlaid on the 3-D projection of the C-130 reconstructed from MSTIL data (original in pseudo-color).

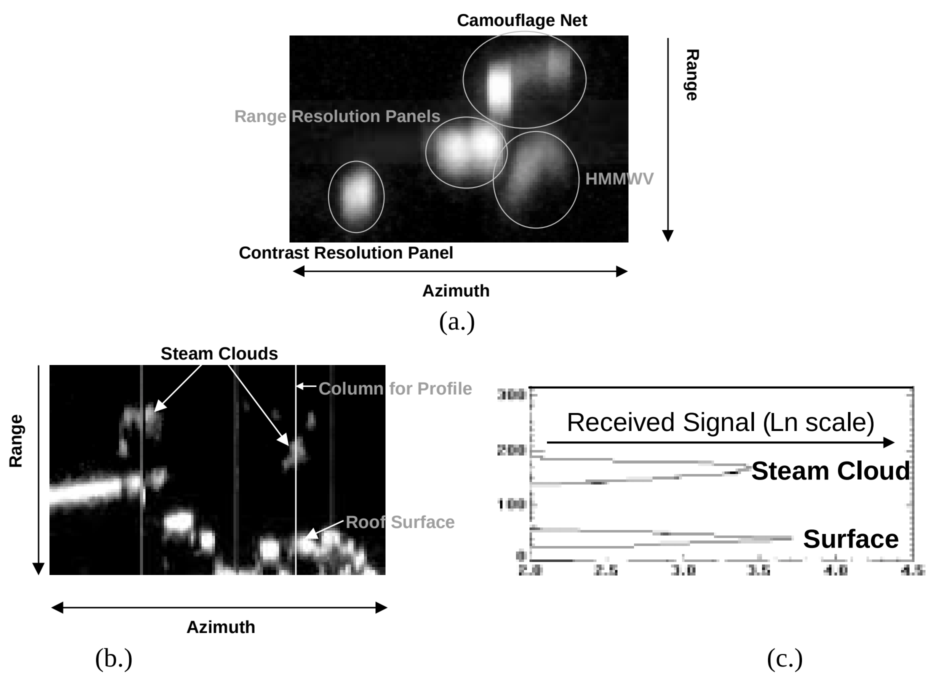


Figure 16. (a.) Intensity-range-azimuth image demonstrating STIL penetrating camouflage. (b.) Intensity-range-azimuth image demonstrating STIL penetrating obscurant (steam) cloud. (c.) Profile along the range direction showing the detectability of both the steam cloud and the roof line surface below it.

3.5 Proposed Brassboard Design and Technology Development

3.5.1 Proposed Brassboard Design

If funded, the next step in the MSTIL development would be to build an MSTIL brassboard with the system parameters designed to meet the missile seeker ATA/R requirements as presented in section 3.2. Figure 17 is a top level block diagram of the proposed MSTIL brassboard conceptual design. Of course, the follow-on system for missile deployment would not require the operator interface and data storage hardware.

The operator control station allows the operator to set the operating parameters such as laser PRF, frame rate, streak tube sweep trigger rate, delay, and duration, the number of data frames to acquire, etc., and to display the real-time intensity and range imagery as data is collected. The operator starts by sending a command to start firing the laser. Then the operator sends a command to start data collection, real-time processing, data storage, and display. The initial timing can be generated either by the laser Q-switch trigger signal or by a signal from a photodiode sampling the outgoing laser pulse. This initial timing signal triggers the delay generator which sets the position of the range window for high resolution range imaging at the required stand-off range to the target. This initial delay can be set by the operator, or can be determined automatically by the system by setting up a coarse range resolution window covering the entire distance from sensor to ground and using the real-time surface algorithm to find the correct delay in the first frame to position the fine resolution range window about the ground in subsequent frames. The sweep delay will be adjusted automatically in real-time to keep the ground area within the fine range resolution range window by feedback from the real-time surface finding processor.

The sweep duration will be set to provide a range window extent greater than the targets' range extents and to provide the required range resolution. The sweep triggering rate will be synchronized with the laser firing rate by the timing controller. It is planned that the laser PRF (10-20 KHz) will be much greater than the intensity-range-azimuth frame rate (~150 Hz). Therefore, many pulses will be integrated on the CCD array for each frame. This will allow the MSTIL to operate with lower energy pulses at higher PRFs to minimize the size, cost, weight, and power requirements of the laser transmitter.

The timing controller will synchronize the CCD array read-out to a frame rate designed to achieve the required resolution along track for the missile's forward velocity. The CCD array is read out, the pixel values are digitized, and the data are routed to the SHARC DSPs for processing.

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The SHARC DSPs first perform bias subtraction based on the receiver calibration image taken in sweep mode, but without illumination by the laser. This step removes artifacts due to non-uniform dark count levels across the image. The SHARC DSPs then perform surface finding based on a Derivative Matched Filter algorithm for finding the peak of the return signal in each column of pixels. This algorithm was developed by Arete Associates for the STIL EOID program. Each column of pixels represents the position of the return in azimuth and each row of pixels represents the position of the return in range. The pixel signal level gives the peak return intensity at the range-azimuth position corresponding to that pixel. After the surface contour is found, feedback is sent to the timing controller to adjust the sweep delay for subsequent frames if the surface is near the edge of the current range window. At the same time, a data reduction processor selects a smaller range window about the surface contour to send to data storage.

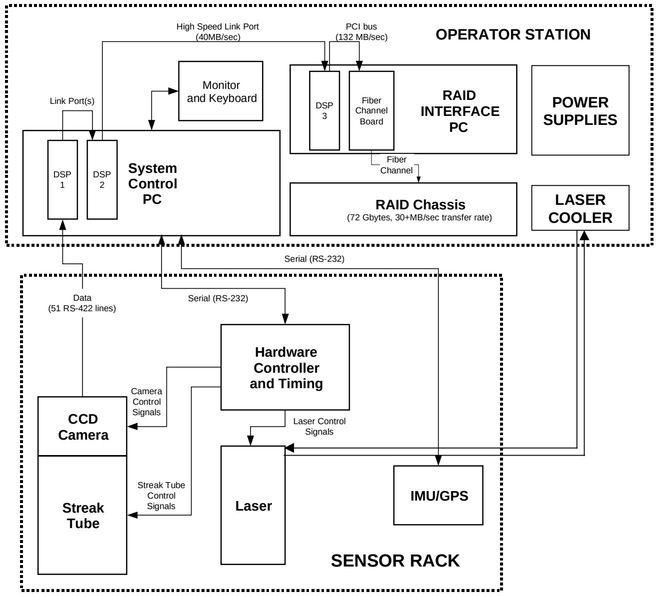

Figure 17. MSTIL Brassboard Prototype Block Diagram.

Several frames are initially collected in a buffer and processed to remove frame-to-frame artifacts which may be caused by pulse-to-pulse timing jitter and energy variations. This buffer only causes an initial delay in displaying of the data since it uses a running median filter to determine the range and intensity corrections required. The first fifteen frames will be used to start the process, causing only a 0.1 second delay at 150 Hz. After the buffer is first filled, the processing can be accomplished at the 150 Hz frame rate as one uncorrected frame is clocked in and one corrected frame is clocked out to the display. The corrected frames are displayed sequentially as a scrolling waterfall display that gives the operator a view similar to one he would have if he were looking out a window below watching the scene pass from one edge of the window to the other as the aircraft flies over the scene. The operator will be able to choose to display the pseudo-color range image or the grayscale intensity image at full resolution in real-time, or he may choose to display both images side by side simultaneously at reduced resolution.

The auxillary data consists of inertial measurement unit (IMU) data, global positioning system (GPS) data, and system diagnostic data (e.g., pulse energy data). The IMU and GPS data are used to perform corrections of artifacts in the imagery due to vehicular motions (roll, pitch, heading, altitude, and speed variations). In order to efficiently use the available processors and inter-frame time, the IMU/GPS corrections are only applied to cut-outs of regions of interest that have been detected as a potentially containing a target. There is no need to IMU/GPS correct the large areas of the scene which do not contain target like objects. The follow-on, compact, advanced development model (ADM) prototype would have real-time IMU/GPS correction, as well as the real-time 3-D image reconstruction planned for the brassboard, that leverage algorithms being developed under the EOID project.

If funded, the MSTIL brassboard will allow captured flight testing to demonstrate achievement of the real-time, 3-D imaging requirements for missile seeker ATA/R. The captured flight tests will test the sensor at altitudes from 1000 ft. to 3000 ft. with slant ranges from 500 m to 1 km at forward velocities of 100 to 130 knots (limited by the aircraft available for the tests). Data from the tests will be analyzed to extract demonstrated image resolutions.

3.5.2 Technology Development

3.5.2.1 Eye Safe MSTIL at 1.5 μm wavelength

Operation of the MSTIL at 1.5 μm wavelength would have the advantages of improved eye safety, better covertness, and better propagation through degraded atmospheres.

Several vendors have developed photocathode materials suitable for streak tube operation at 1.5 μm (e.g., Hamamatsu and Intevac[7]).

We also plan to assess other methods for streak tube operation at 1.5μm, such as up-conversion phosphors.[8]

Solid state transmitter lasers operating at 1.5 μm using Raman cells or Optical Parametric Oscillators have been developed over the last decade or so for terrestrial applications. Compact sources of this type suitable for integration with STIL are discussed in the next section.

3.5.2.2 Size/Weight Reduction

Compact, efficient source lasers are needed for MSTIL for both the near term 532 nm operational wavelength and for the mid-term 1.5 μm operational wavelength. A frame rate of 150Hz will provide sufficient along track resolution to meet missile seeker ATA/R resolution requirements at the missile cruise speed of 200 knots (103 m/s). This frame rate would require a laser pulse repetition frequency (PRF) of at least 150 Hz, and for single pulse detection, about 40 mJ output for 1 km slant range for the brassboard design. Although this performance level is achievable with current flash lamp pumped Nd:YAG lasers, these lasers are larger, heavier, and more expensive than the higher PRF diode pumped Nd:YAG and Nd:YVO_4 lasers with the same average power. The higher efficiency of the high PRF diode pumped lasers also leads to lower power and cooling requirements.

The Air Force and the Aerospace industry have invested in the development of high average power, high PRF, compact diode pumped solid state lasers for applications such as missile terminal guidance. High PRF diode pumped Nd:YVO_4 lasers that meet the average power output requirements (~ 6 W) for the missile seeker ATA/R missions have been developed. Lite Cycles and Cutting Edge Optronics (CEO) each offer compact diode pumped Nd:YVO_4 laser designs with average output powers of 15 W to 20 W at 1.06 μm that can provide 6 W to 10 W average power output at 10 KHz to 20 KHz PRF in < 10 nsec pulses at 1.5 μm using an OPO crystal or at 532 nm using a doubling crystal. Figure 18 shows a compact, air-cooled, diode pumped Nd:YVO_4 laser developed by CEO for missile terminal guidance. The image is almost actual size (diode laser pump not shown).

The streak tube receiver can take advantage of these lasers' high PRF to accumulate pulses on the CCD and read out the improved signal-to-noise ratio images at a lower frame rate (~150 Hz). Streak tubes with up to multi-megahertz sweep retriggering rates are routinely used for pulse integration in time-resolved spectroscopy.

Figure 18. Cutting Edge Optronics compact diode pumped Nd:YVO_4 laser source suitable for MSTIL.

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[7] Costello, K., V. Aebi, G. Davis, R. LaRue, and R. Weiss, "Transferred electron photocathode with greater than 20% quantum efficiency beyond 1 micron," SPIE Vol. 2550, 1995, pp. 177-188.
[8] Hou, Xun, L. Du, W. Fan, L. Niu, X. Zhang, Z. Chang, M. Gong, W. Zhao, and B. Yang, "A ps infrared streak camera with an up-converting material," SPIE Vol. 3516, 1999, pp. 160-166.

The receiver can also be made more compact. Compact streak tubes with tens to hundreds of picoseconds response times are now available (Figure 19). Arete Associates plans to develop the electronics necessary to integrate a compact streak tube into a compact STIL system.

Figure 19. Commercially available Compact Streak Tube. Streak Tube Dimensions: 8.0 cm (3.15 inches) long by 6.5 cm (2.56 inches) in diameter.

4.0 STIL FOR TERRESTRIAL MAPPING

During the course of Arete Associates' initial streak tube development contract with ONR, an opportunity arose to examine the utility of the STIL technology for use in airborne remote sensing. The first opportunity was a proof-of-concept imaging experiment for assessing biomass in Southern Bluefin Tuna. This experiment took place in South Australia during March-April of 1997, following a rapid IR&D effort that transitioned the laboratory STIL prototype to an airborne breadboard configuration that was flown in Southern Arizona in February of the same year. Although the objective of this project was 3-D imaging of in-water targets from an airborne platform, the first data collected were for terrestrial scenes, as these were more accessible for the first flights near Tucson, AZ. This initial terrestrial data indicated a clear potential for terrestrial surveillance using the ASTIL system.

Late in 1998, having explored both bathymetric and terrestrial imaging applications in early airborne tests, Arete Associates committed additional IR&D funds to further examine terrestrial mapping using the ASTIL system. Both the bathymetric and terrestrial mapping applications indicated viable markets, but the terrestrial application featured fewer barriers to entry for new, emerging technologies. The goal of this research was to collect synoptic Real-Time Kinematic (RTK) Differential GPS (DGPS), i.e., RTK-DGPS, position data, Inertial Measurement Unit (IMU) attitude data, and ASTIL 3-D image data over simple terrestrial features, and attempt to map these features geodetically in three dimensions based on the fusion of GPS, IMU, and LADAR data streams. Experiments conducted in 1999 were encouraging, demonstrating meter scale lateral registration and decimeter scale elevation registration capability, and it is anticipated that decimeter scale registration in all three dimensions will be obtained in the early CY2000 experiments because of recent improvements in the system's IMU configuration.

4.1 Scenario and Requirements

Operations for terrestrial survey require an ASTIL sensor integrated with commercial-off-the-shelf (COTS) RTK-GPS and IMU equipment, and minimal ground support for survey (fiducials, as needed) and analysis (map generation). Once the system is installed on an aircraft and the area of interest is identified, the ferry flight can be made to the target region and the mission plan can be executed.

The requirements for airborne terrestrial mapping vary greatly with application, and derive principally from discussions with corporate collaborators in this market. The most stringent applications require sub-decimeter to decimeter scale geodetic resolution and accuracy in all three dimensions. Typical examples of these applications include commercial surveys of ongoing real estate development and surveys of road and highway projects. Less stringent, and more common requirements are those typical of aerial photogrammetry applications that require sub-meter elevation resolution and 1-5 meter lateral resolution. Typical examples of these applications include municipal land use surveys and the National Imagery and Mapping Agency (NIMA) surveillance efforts aimed at

general terrain characterization. The least demanding applications are also more typical of standard photogrammetry surveys, where meter scale resolution in elevation and multi-meter scale resolution and accuracy are acceptable for registering features laterally. Examples of this class of data are that of forestry surveys and large scale surveys such as the NASA Shuttle Radar Topography Mission (SRTM) using an interferometric synthetic aperture radar (IFSAR) to provide 30 meter x 30 meter lateral spatial sampling with 16 meter absolute vertical height accuracy, 10 meter relative vertical height accuracy, and 20 meter absolute horizontal circular accuracy.

Based on current market data, the application area best served by the ASTIL technology is that of the high resolution three dimensional geodetic survey market. The requirements for a typical application in high resolution geodetic survey are

1. **Search Area**: 10 km^2 per hour, with a 20% coverage redundancy, assuming a vehicle speed of 60 m/s (typical light twin engine aircraft speed) and a FOV of 25-30 degrees.
2. **Resolution**: Decimeter (10-30cm) elevation and cross-track resolution and sub-meter along track resolution, leading to 0.5 mrad cross-track angular resolution and a laser PRF of 100-200 Hz depending on mission planning and execution. Less than 100 Hz PRF performance is acceptable if additional coverage redundancy is feasible.
3. **Acquisition Range**: 200 – 500 m standoffs, depending on the required resolutions.
4. **Real-time 3-D Image Update**: While not a strict requirement for commercial mapping, it is helpful to use a real-time detection algorithm to resolve and display the ground features in a continuous scroll elevation display, updated at the system PRF (e.g. 100-200 Hz). Real-time 3-D image update at 5-30 Hz or greater rates is required for some military applications of terrestrial mapping as discussed in section 4.5.

4.2 ASTIL Breadboard Description

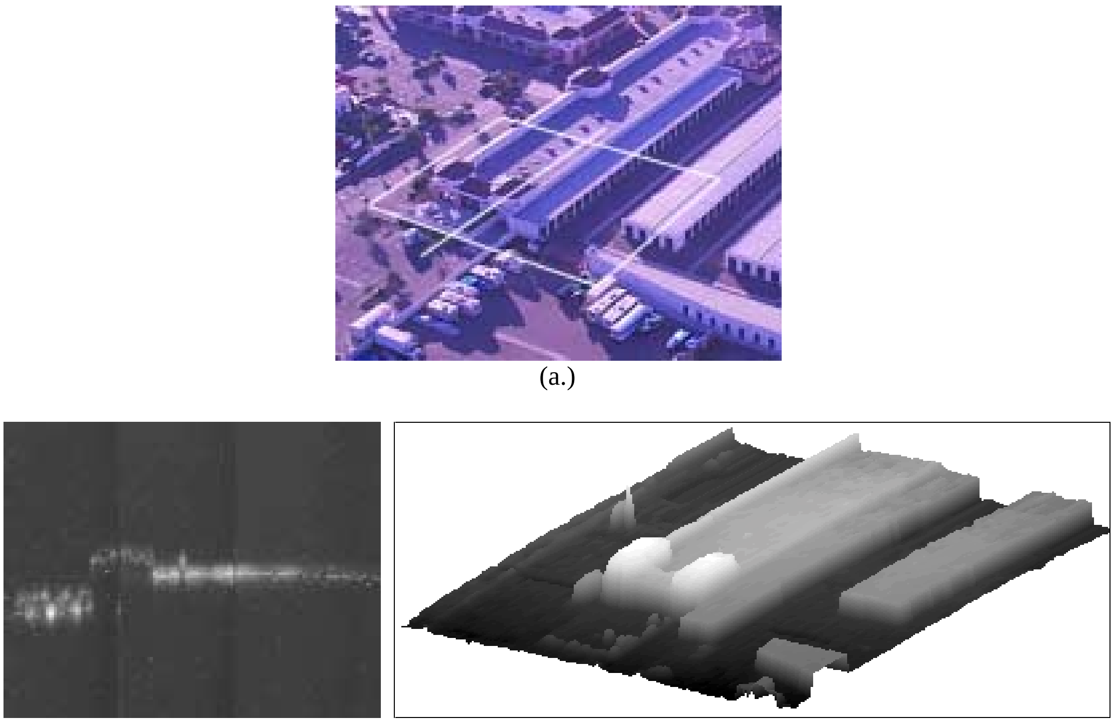
The early ONR-funded laboratory STIL experiments utilized a Hamamatsu C4187 streak camera system, a fiber-coupled COTS front-end optical assembly and a lens-coupled, cooled CCD camera from Princeton, all integrated on a portable optical bench with attendant diagnostic optical assemblies and scan mirrors (for simulating platform motion). The laser used was a Big Sky CFR400 with a 10 Hz PRF. The ASTIL breadboard system retained the Hamamatsu C4187 streak camera, but the balance of the components were replaced in order to allow for a higher degree of ruggedization, and to facilitate the higher data rates required by the 100 Hz laser PRF. (The replacement components were listed in the MSTIL breadboard description in section 3.2). The current prototype ASTIL breadboard's parameters and the anticipated operational system's parameters are shown in Table 2.

Table 2. ASTIL System Parameters for prototype and (anticipated) operational systems

Parameter	Prototype ASTIL	Anticipated Operational ASTIL
FOV	12.6 degrees (azimuth)	30 degrees (azimuth)
Cross-track resolution	1.0 mrad	0.5 mrad
Along-track resolution	0.6 – 2.0m	0.3 – 2.0m
Range Accuracy	10cm	10cm
Maximum Range	500m	500m
Transmitter Pulse Energy	12 – 100 mJ	10 mJ
Transmitter Average Power	1 – 3W	2W
Transmitter Pulse Width	10 ns	10 ns
Pulse Repetition Frequency	30 Hz	200 Hz
Wavelength	532 nm	532 nm
Clear Aperture	100 mm	100 mm
Eyesafety	NOHD: 70 – 200 m	NOHD: 70 m
Real-time map generation	Offline	Scrolling map, PRF update
Map product latency	1 day post-mission	Quick-look 0 hrs post-mission; deliverable maps 2 hours post-mission
Image data format	256 range x 256 azimuth	128 range x 512 azimuth

4.3 Terrestrial Mapping Tests at Oxnard, CA

Flight tests were conducted in 1998 and 1999 near the Oxnard Regional Airport in Oxnard, California. Data collected in 1998 demonstrated, conceptually, the capability to map terrestrial features in three dimensions as shown in Figure 20. However, the IMU and RTK-GPS systems were not fully integrated for those tests. Tests in 1999 succeeded in integrating the IMU and RTK-GPS systems with the ASTIL data, but marginal IMU performance allowed only meter scale lateral and decimeter scale height geolocation, and precluded a demonstration to the limiting performance of the system (sub-decimeter). Experiments in early CY2000 are anticipated to yield the desired decimeter scale performance in all three dimensions now that IMU difficulties have been identified and corrected. The next two sections describe more fully the tests that have been conducted to date.



(a.)

(b.) (c.)

Figure 20. Terrestrial image data from 1998 tests. (a) Aerial photo of the buildings being imaged. (b) Single laser shot showing raw intensity-range-azimuth data for one line image, indicated by a single white line in (a). (c) 3-D Range image of area outlined by the square in (a) reconstructed from the individual intensity-range-azimuth frames (Range is mapped to grayscale with white being the closest range).

4.3.1 Oxnard Test Setup

The ASTIL system was integrated into a Partenavia Explorer at the Aspen Helicopter facilities in Oxnard, California. Figure 21 shows the installation of the ASTIL sensor rack located mid-body in the Partenavia. The operator faces aft in this setup and views a monitor in the operator station that is directly aft of the sensor rack. A Boeing C-MIGITS (**C**oarse - **M**iniature **I**ntegrated **G**PS/**I**NS (Inertial Navigation System) **T**actical **S**ystem, where coarse refers to the coarse acquisition GPS engine) IMU was installed on the sensor rack directly adjacent to the ASTIL optical axis. It was fed by a L1/L2 GPS antenna that also provides the signal for the GPS-derived sensor time base (in the ASTIL computer chassis), and the signal for the R4000-series Trimble DGPS receiver used for precise geolocation of the aircraft center of gravity as a function of time. A boresight video camera provided a real-time view of the sensor FOV in order to help with aircraft track alignment and operator data collection sequencing.

The C-MIGITS INS/IMU module consists of solid state accelerometers and digital quartz gyros. This INS/IMU experiences the same limitations as all inertial based guidance and navigation systems. The main

limitation is drift. The drift in the accelerometers and gyros causes a degradation in the position solution with time. However, the C-MIGITS system incorporates an integrated GPS engine which provides a time-varying position solution that is coupled with the INS position solution via a 28-state Kalman filter to correct for accelerometer and gyro drift to provide a high accuracy position solution that does not degrade with time. Therefore, the system accuracy is mainly dependent on GPS accuracy (e.g., 100 m for commercial-GPS, 7 m for the military P-code GPS, and <1 m for DGPS). For terrestrial mapping, we use a DGPS system to provide the most accurate 3-D image reconstruction and geolocation obtainable with the system.

Figure 21. Photograph of the ASTIL breadboard on a Partenavia Explorer for flight tests.

While airborne data are being collected from the ASTIL sensor, the C-MIGITS IMU unit, and the R4000-series DGPS receiver on the aircraft, an additional R4000-series DGPS receiver collects fixed-point reference data on the ground. Post-processing of the two DGPS receiver data streams provides highly accurate geolocation of the aircraft center of gravity. This accurate position data combined with the attitude data from the IMU allows the ASTIL 3-D imagery to be mapped geodetically to the desired precision.

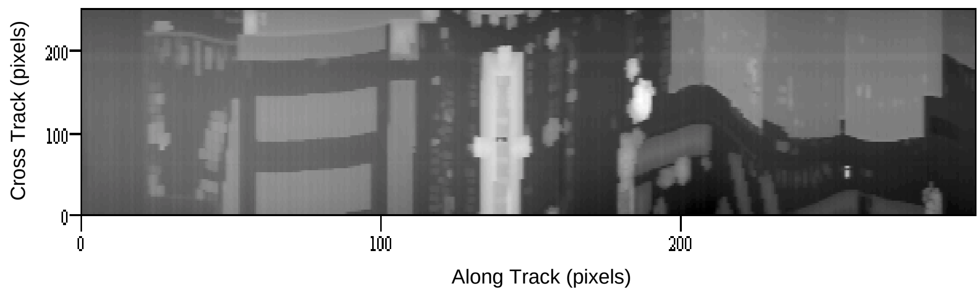
4.3.2 Oxnard Test Results

Figure 22 shows a segment of ASTIL data before and after RTK-GPS and IMU registration correction, indicating good correction of the image for the aircraft attitude variations, and good registration with the fiducial points marked by crosses in the figure. The objects of interest are several buildings at the Oxnard airport. Several corners of these buildings were surveyed to provide the fiducial points for estimating the registration errors for the experiment. Despite the difficulties experienced with the IMU, the 1999 Oxnard data yielded decimeter scale elevation and meter scale lateral geodetic location accuracy, as shown by the elevation and lateral offsets between the fiducials and the reconstructed ASTIL data listed in table 3. From this data, the root-mean-square offsets between the fiducials and the ASTIL data are 0.757 m north-south, 0.945 m east-west, and 0.187 m in elevation.

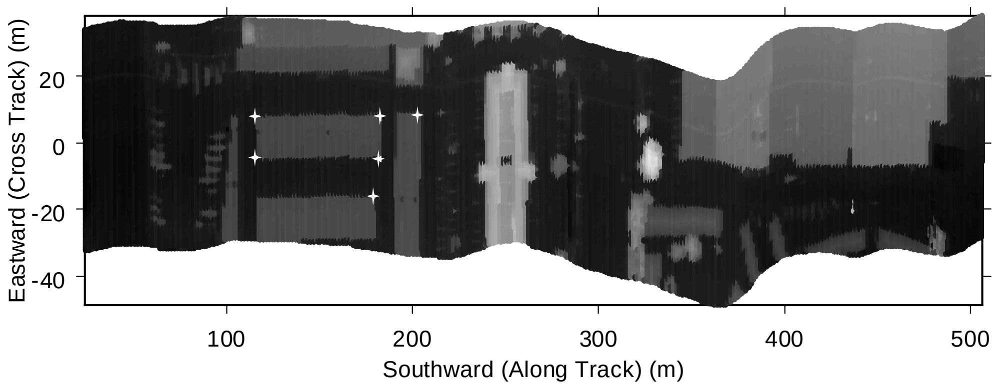
4.4 Development and Commercialization Plans

The IR&D efforts for CY2000 will focus on completing the demonstrations begun in 1999 by producing marketable demonstration imagery registered to decimeter scale accuracies in all three dimensions. These registered images are anticipated to be available in the second quarter of CY2000, and will be used to secure early contract work with existing clients that have expressed an interest in the data from the ASTIL sensor. Arete Associates will work with a commercial survey firm to market the ASTIL terrestrial mapping data for commercial survey applications. Early customers are anticipated to be municipalities in need of high resolution data for select geodesy work, government agencies in need of highway construction monitoring, power companies in need of structure surveillance, and construction firms wanting to rapidly obtain survey data for development projects. Some contract

opportunities are already being considered with governmental and commercial entities, but actual survey activity is not anticipated until the fourth quarter of CY2000.



(a.)



(b.)

Figure 22. (a.) Grayscale range map reconstructed from ASTIL data prior to RTK-GPS and IMU registration correction. (b.) Grayscale elevation map (tangent plane view) after RTK-GPS and IMU registration correction (crosses show locations of the ground surveyed corner locations (fiducials)).

Table 3. Lateral and Elevation Offsets between Fiducials and Corresponding Corners shown in Figure 22.

Corner Reference No.	Offset North (m)	Offset East (m)	Offset Elevation (m)
1	-0.7574	-1.437	-0.0224
2	0.6806	-0.2231	0.0607
3	0.9868	0.7043	-0.1081
4	-0.4311	-0.2098	0.2104
102	0.5789	-1.4867	0.3602
107	-0.9537	-0.7056	0.1443

4.5 Potential Military Applications of Terrestrial Mapping and Geolocation

The STIL system can be deployed on ground-based and aviation (both fixed and rotary wing) platforms. In flights over areas of interest, STIL can produce high resolution 3-D imagery with precise geolocation of buildings, vehicles, troops, fortifications, etc., to produce updated 3-D, GPS true maps in real-time for intelligence imagery, for reconnaissance and surveillance to update enemy troop and other assets locations and configurations, for target acquisition and aided recognition combined with precise geolocation for hand-off to weapons platforms for attack and force protection, and for battle damage assessment after attack. We are developing algorithms and hardware to produce the 3-D imagery in real-time so that reconnaissance, surveillance, intelligence, mapping, targeting, and battle damage data can be updated in real-time. If our R&D efforts to reduce the size and weight of STIL (see section 3.5.2.2) are successful, then STIL would also be compatible with deployment on unmanned aerial vehicles (UAVs). From ground-based platforms (e.g., as an upgrade for the Hunter Sensor Suite (HSS)), STIL can perform these same missions from a different perspective. In addition, the army has programs to develop a multi-function

laser system to provide wide FOV terrain mapping, narrow FOV target profiling (for aided target recognition), and target ranging and designation from ground platforms. Using zoom lenses, STIL could perform the terrain mapping, target profiling, and target ranging functions, and by using the 1.06 μm output and controlling the laser PRF, STIL could provide target designation. Since STIL can be configured to operate over narrow to wide FOVs, STIL's area of coverage and resolution can be varied for multiple functions and to meet various mission needs.

In both combat and training missions involving low level and terrain following (nap of the earth) aircraft operations, the services require terrain awareness and obstacle avoidance warning systems. STIL's ability to operate at high spatial resolution in three dimensions over a wide azimuthal FOV makes it well suited for these missions.

In addition to the intelligence and combat missions described above, there are also non-combat military applications for STIL's ability to provide accurate, high resolution digital elevation maps. Military training installations have a requirement for current and accurate digital elevation maps to aid in management decisions concerning the site such as determining areas excluded from training due to excessive slope, and to determine drainage patterns and locations susceptible to erosion. Airborne LIDAR derived DTEDs can be used to provide 2 meters or better grid spacing.[9] In addition, all military installations require accurate survey data for building and road construction. The Airborne STIL can provide faster coverage while maintaining accuracy for large area construction projects compared to conventional methods.

5.0 SUMMARY AND CONCLUSIONS

Arete Associates' patented Streak Tube Imaging LIDAR (STIL) is a unique application of commercial-off-the-shelf technologies to provide high resolution, scannerless, wide field-of-view, active 3-D imaging. The initial development of STIL was supported by the Office of Naval Research for underwater mine detection and identification. The STIL system has progressed to entering the Engineering, Manufacturing, and Development phase for this application.

In parallel with the development for ocean applications, Arete Associates initiated the development of the Airborne STIL (ASTIL) for commercial terrestrial mapping and bathymetry. Recent tests of the ASTIL over southern California have demonstrated mapping accuracy at the meter scale laterally and at the decimeter scale in elevation. Recent improvements in the IMU should provide geolocation accuracy to the decimeter scale in all directions. ASTIL flight tests in early CY2000 are expected to produce decimeter scale geolocation accuracy in all directions. ASTIL is poised for commercialization for terrestrial mapping and bathymetry within about a year.

Recently, Arete Associates received funding from the Air Force to extend the terrestrial applications of STIL to the missile seeker ATA/R mission. The Phase I field test results presented in this paper demonstrate the capability of the STIL concept to meet the 3-D imaging requirements for missile seeker ATA/R.

Further development of the STIL system is required to implement real-time processing for terrestrial applications, to improve the resolution from 128 range by 512 azimuth pixels to 256 range by 1024 azimuth pixels, to make STIL compact and lightweight, and to shift STIL operation to the 1.5 μm wavelength regime for improved eye safety, covertness, and atmospheric propagation. Technologies that will enable these improvements in the STIL system are either commercially available or currently in development.

6.0 Acknowledgements

The authors thank their colleagues Glen Redford and William Ryder of Arete Associates for their contributions to this project. We also thank Robert Williams, Bien, and Frost (RBF) for providing DGPS equipment and GPS data reduction in support of the Terrestrial mapping tests. We thank the Air Force Munitions Directorate for supporting the Phase I SBIR project for applying STIL to missile seeker ATA/R.

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[9] Foote, Harlan P., K.L. Steinmaus, and P.E. Nissan, "A Comparison of LIDAR Derived Terrain Data with Conventional Techniques," paper presented at the Seventh Annual Integrated Training Area Management (ITAM) Workshop, Yakima, Washington, 1998.